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**Gravity Recovery and Climate Experiment Satellite
Thermal Model**

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G.R.A.C.E. Satellite Thermal Model

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I developed a thermal model of the Gravity Recovery and Climate Experiment satellite for the Center for Space Research to use in verifying their thermal models and for developing the next generation of satellites for their experiments. I chose COMSOL to model the satellite and used ProEngineer and 3Ds Max to generate the mesh from a .STEP file provided by DaimlerChrysler. I adjusted the model based on previous computer models and actual telemetry data from the GRACE satellite provided from 2002 through 2008. Using the model, I developed a sensitivity analysis of the satellites key thermal environment components and used that to recommend design changes for the next generation of satellites. Special attention should be given to redesigning the Star Camera Arrays and the heat transfer between the Main Equipment Platform and the Radiator.

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Chapter 1: Problem Statement

The GRACE satellite has experienced unexplained temperature fluxuations since the satellite was launched in 2002. The satellite is also operating at significantly colder temperatures then predicted by previous models, forcing survival operation. It's unknown whether these conditions are caused by a design flaw or a flaw in the thermal modeling software previously used to analyze the GRACE system. Additionally, the batteries have reduced in capacity to the point where normal function is no longer an option and a model to predict the thermal environment including all these factors does not yet exist. The goal of this research is to develop a thermal model of the GRACE satellite which more accurately predicts the satellites thermal environment and explains both the fluxuations and colder operating conditions.

When the CSR makes a request for GRACE 2 funding, they will need to know if the original GRACE satellites are a thermally sound design or if significant redesign will be required to maintain an appropriate thermal environment for the instrumentation.

If the CSR concludes that a redesign will be necessary, then an up to date computer model will be necessary to assess the effects of any design changes on the satellites thermal profile. A model accurate enough to predict the current thermal environment of the GRACE satellite and robust enough to support future design work will be required to move forward with GRACE 2.

Previous Thermal Analysis

Document GR-DSS-TN-0004 describes the preliminary thermal analysis of the GRACE satellite by Daimler-Benz Aerospace used to test an initial design of the GRACE

satellite. This study is notable for laying out the main case studies used to benchmark the GRACE satellite design. The case studies, labeled Hot 1, Hot 2, Hot 3 and Cold 1, Cold 2, Cold 3 have been repeated through all the previous thermal analysis and has also been used as a benchmark for my research which allows a quick and insightful review of the various GRACE satellite thermal models since 1998.

Some of the most important aspects of this document are the descriptions of the design baselines. The satellites baseline (near zero heater input) was designed around a Beta angle of 73° to minimize thermal distortion and heater power. The most significant part of the document pertaining to this research was the description of how temperatures are stated for time varying case studies and how albedo is handled in time orbiting case study.

“The following tables Table 9 2-1 and Table 9 2-2 show the analyzed orbital mean temperatures for all load cases, sorted by node numbers and by node labels. The temperatures are as computed without any margin”

“For both cases the earth radiation is modulated around its mean value by a harmonic swing of 10% of the orbital average. Modulation frequency and orbit frequency is identical. The Maximum earth shine is concurrent with the maximum albedo for the cold case, while for the hot case the earthshine peak occurs when the nadir radiation is sunlit. Both approaches leads to the respective maximum overall temperature swing.”

For the most part, this document was purely historical but it set a number of precedents on presenting the data from transient results which were carried through to

future analysis. The shape of the GRACE satellite studied in this preliminary document has also been changed to be significantly simpler.

Document GR-DSS-TN-0009 was created to identify the most important design aspects for the development of the GRACE satellite. This analysis was key to creating my updated COMSOL model and many of the material, environmental and thermal parameters I used came from the 1999 analysis. Some of the most important parts of this document have been the naming scheme laid out in the beginning using orthographic projections of the satellite. This scheme was used in my COMSOL model to maintain consistency between the thermal analyses and make it easier for Center for Space Research (CSR) personal to understand the results of this research with respect to previous work.

Again we see the Thermal Design Load Cases laid out in the 1998 document but somewhat more comprehensive. Now included are survival mode and an additional Hot Case 4 to analyze thermal distortion in the baseline case.

Probably the single most important section of the 1999 analysis document was the “Thermal H/W Description” section which contained a detailed description of most systems of the satellite along with important notes and physical designs. This was the section I focused on when designing my COMSOL model.

Chapter 2: Thermal Analysis Tools

Selecting a modeling program was a difficult proposition at the beginning of this research project. Any program would need to accurately reproduce the GRACE satellite but also allow experimentation for the future design of the GRACE 2 satellite. This almost necessitated a CAD file import feature along with access to more than simple heat transfer physics in case structural or electromagnetic analysis would be of interest in the future. The ability to run time dependent case studies accounting for a complex arrangement of heaters along with multiple external thermal radiation was also considered.

NEVADA was a program developed by NASA to analyze radiation heat transfer in satellites. NEVADA was a simple conduction-radiation solver that had been validated through many years of industry and academic testing. Available versions had very limited capabilities to import 3D models which would make designing the whole satellite in the program tedious and difficult. The 1998 model of the GRACE satellite used NEVADA and a shell of the satellite to get rough estimates for the satellites shapes, materials, and the thermal environment. Another important aspect of NEVADA was the ability to calculate radiation heat transfer with independent emission and absorption surface properties. Material properties were available through extensive material libraries created by NASA. Unfortunately support for NEVADA has been canceled and the rights to the code transferred to a private corporation making the old, freely licensed versions difficult to find.

ANSYS Fluent was considered, but the lack of a simple user interface and a difficult CAD import system left it low on the list of software. The University of Texas at Austin maintains an up-to-date license for Fluent and the High Power Computing system (HPC) also supports Fluent. But a radiation solver was added into the program and the code was considered sub-optimal.

Thermal Software System (TSS) from SpaceDesign looked like a fantastic program for this research. Developed and eventually sold by NASA to a private organization, TSS was designed from the ground up for space based heat transfer problems. It included a simple CAD interface and many unique methods of solving problems in space involving albedo, umbra and solar weather. The primary difficulty was expense. The University of Texas at Austin did not have an up-to-date license and the cost was prohibitive. Future investment for space research would be wise to consider this program.

The selected program was COMSOL Multiphysics. This program coupled a multiphysics differential equation solver with a simple user interface and CAD import system. The University of Texas at Austin had an up-to-date license which would be fiscally prudent. It was also available on the HPC and online through Citrix if I needed to work at the CSR or elsewhere. COMSOL's ability to work with .STL files also benefitted this research. My preferred 3D manipulation software works especially well with .STL files which are highly compatible between CAD programs. The ability to quickly import,

modify and configure new satellite components without complex re-meshing should fit the needs of future researchers. Additionally, COMSOL's multiphysics package would allow researchers in almost any branch of science or engineering to quickly adapt this model for future studies. This combination of traits led to the selection of COMSOL as the program for this research.

Chapter 3: Creating the Model in 3DS Max

A .step file was provided by Dr. Bettadpur of the 3D model used during the construction of the GRACE satellite system. This model included all major structural components and systems with a resolution all the way down to the individual solar panels on the exterior of the satellite. However, the model did not include comprehensive wiring, a fact which played heavily into the later decision to not include wiring in the new COMSOL model.

ProEngineer was used to open the .step file and review the detailed list of components. Using the previous computer models as a reference, important satellite components were isolated for further review. Having the design drawings also allowed our model to include detailed structural components which should greatly increase the fidelity of the heat transfer model over previous computer models. Components such as wires, fasteners, small tubing, etc., were excluded due to technical limitations on computer power. Given enough computer power along with the full .step file, future COMSOL models could technically include every component in the GRACE satellite. Due to the limited time and resources, this was not an option available on this project. The selected .step file components were then simultaneously exported as individual .stl files for re-assembly in 3D Max. Exporting all the components at once was extremely important because it maintained the global coordinate system; otherwise the individual components would not re-assemble in their proper locations.

Modification of Model for COMSOL with 3Ds Max

The imported .stl files would first have to be geometrically simplified for the radiation analyzer to be able to converge to a solution in a reasonable time. This process was facilitated by 3D Max 7 from Autodesk, one of the premier mesh editing programs on the market. Each part could take anywhere from 1 to 10 hours to import, clean and debug before being fully recognized by COMSOL. The advantage of this system however is, when the part has been completed, no additional editing is needed in COMSOL meaning all the modeling work will be completed up front.

One of the most important functions of 3Ds MAX was the ability to quickly remove thermally insignificant features from the GRACE satellite model. Small holes, wires, protrusions, slots, and other small features that could be isolated from the main body of a part were removed leaving a clean surface better suited to COMSOL's meshing software. The subjectivity of this process was reduced by following a set of guidelines based on the principals of conductive and radiative heat transfer.

$$\rho c_p \frac{\partial T}{\partial \tau} = \nabla^2 (kT_k) + \sigma A_k \sum_{j=1}^N (T_k^4 - T_j^4) F_{k-j}$$

- 1) Would the removal of this feature significantly affect the radiative surface area A_k of any remaining or important parts?
- 2) Does this feature play an important role in aiding or abating the heat transfer between any two parts? (i.e. does it affect F_{k-j})

- 3) Will the removal of this feature significantly alter the thermal mass ($\rho c_p v$) of any part or the satellite as a whole?
- 4) Is this feature of any engineering importance to the GRACE satellite? (ex. A small sensor or sensitive component)

In the process of simplifying a part a variety of small mesh errors were often created that, if left unchecked, would prevent COMSOL from identifying the .stl file as a cohesive component. Correcting mesh normal, intersecting faces, overlapping edges, isolated vertices and redundant faces was completed with a variety of .stl error checking features in 3Ds Max. Importing a piece into COMSOL might identify an error in a specific section and careful inspection with 3Ds Max would often locate a simple problem to be repaired.

Models in 3Ds Max were run through a variety of mesh simplification steps to achieve the highest fidelity mesh with the lowest polygon count. This was key to developing a detailed model requiring minimal computational resources. I used a combination of 3Ds Max Optimize, Smooth, Tessellate, and Vertex commands along with external programs like MeshLab and Simplex. The dimensional fidelity of each piece was maintained within +/- 2% of the original dimensions while reducing the vertex and polygon count by multiple orders of magnitude. Additional adjustment to vertex and polygon counts was done with COMSOL's limited import features and meshing system.

Chapter 4: Creating the Model in COMSOL

With the .stl files completed in 3Ds Max, I began importing them individually into separate COMSOL files to check their dimensional accuracy and to ensure there were no issues loading the models. If an error occurred upon importing the model, the source of the error was identified and repaired in 3Ds Max or a separate mesh editing program. Once all the errors had been checked I imported all the .stl models into a single COMSOL file to begin the thermal modeling. Additionally, I have renamed the components based on document GR-DSS-TN-0009 Issue 2, pages 7-9 of 67. Along with a component view pulled from the GRACE web site available at

<http://www.csr.utexas.edu/grace/spacecraft/config.html>.

This change will make it significantly easier to apply physical properties and makes it easier for CSR workers to understand the COMSOL model.

The next step was to import all the .stl files into a single COMSOL model. Minor adjustments in component positioning and scaling were performed to purposefully overlap components. Some simple satellite components like the gyros and boxes were added using COMSOL's built in geometric creation tools. All the components were placed into an "assembly" and that completed the importation process.

Creating and Applying Surface Properties

With all the components accounted for, I moved on to the next segment of the COMSOL model; applying material properties. Specifying material properties for a

surface or object is incredibly simple in COMSOL. Simply clicking on the surface or object and designating a new material takes seconds. The major limitation is knowledge of the surface properties. Radiative properties of materials were specified without reference to the method of analysis or uncertainties. Absorptivity in the visible range wavelengths and emissivity in the infrared range wavelengths were specified in the initial documents for the second computer model by DaimlerChrysler. The values are also subject to suspicion because they were measures in 2002 before the launch of the satellites and there is very little data on how materials age in space. A drift in the radiative surface properties $\pm 20\%$ is not unheard of in space based applications due to ionizing radiation and material age.

The emissivity was taken as equal to the absorptivity due to limitations in COMSOL 4.0a. This was shown to cause some errors when comparing with the satellite telemetry but those temperature differences are mostly on the exterior surface of the satellite which tends to be very insulated from the internal thermal environment. Visible radiation is most important on the exterior surface of the satellite subject to solar irradiation. Thermal radiation is more important on the interior of the satellite and the radiator equalizing temperature with the earth.

Surfaces that were thermally irrelevant were given the emissivity of 1.0 to minimize computation time spent on internal reflections. This includes exceedingly thin portions of the satellite, the interior surfaces of holes and the adjacent sides of satellite components. This significantly reduced the solution time while maintaining the fidelity of the model.

Creating and Applying Volumetric Properties

One of the most complicated undertakings in this model was accurately applying physical properties to the individual components which would allow for the creation of a transient model. Various documents, particularly GR-DSS-TN-0009 and GR-DSS-IP-001 were used to find applicable physical parameters. To fully specify a component in time we are required to address the transient side of the heat equation.

$$\rho c V \frac{\partial T}{\partial t} = k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2}$$

Here we see density (ρ), specific heat capacity (c), and volume (V). Although property data may exist for the materials, because we are creating replacement components made of simple shapes it is only important that the product of the three terms be accurate.

$$\rho_{real} * c_{real} * V_{real} = \rho_{model} * c_{model} * V_{model}$$

This significantly simplifies the problem because Volume has already been given from the 3Ds MAX model of our component. We use the fact that $\rho * V$ is simply the mass listed in GR-DSS-TN-0009 and related documents, and $\rho * c * V$ is similarly just the thermal mass listed in the same document. Now it's a simple matter of division as long as the data is available.

$$\text{density } \rho \left(\frac{Kg}{m^3} \right) = \frac{\text{mass } \rho * V (Kg)}{\text{Volume } V (m^3)}$$

$$\text{Heat Capacity } c \left(\frac{J}{Kg * K} \right) = \frac{\text{Thermal Mass } \rho * c * V \left(\frac{J}{K} \right)}{\text{Mass } \rho * V (Kg)}$$

Heat dissipation was provided for the components listed in GR-DSS-TN-0009 Issue 2, page 38 of 67 based on the volume of the *modeled* component imported into COMSOL from 3Ds MAX 7. Within COMSOL's "Heat transfer" module, a volumetric power dissipation was created and applied to each component according to the following formula. The volumes of the 3D objects were nearly identical to the actual satellite model, more importantly, the thermal mass of each satellite component is identical to the design documents.

$$\text{Power Dissipation} \left(\frac{Watts}{m^3} \right) = \frac{\text{Power Dissipation (Watts)}}{\text{Component Volume 3Ds MAX } (m^3)}$$

$$\text{PCDU Volumetric Heat Generation} = \frac{8W (\text{Cold Survival } \beta = 90^\circ)}{0.0175m^3 (3Ds MAX)} \approx 475 \left(\frac{W}{m^3} \right)$$

This method is simple to implement and has been made easier by COMSOL allowing the entry of mathematical equations instead of simple values. I have left the equations for each component in (watts/volume) so future researchers can simply input the total power dissipation as a function of time without needing to reference the component's volume.

CFRP covered aluminum honeycomb of varying thickness are one of the main components of the satellite. The main equipment platform, dividers and parts of the solar

panel array are comprised of this honeycomb structure and proper characterization is vital to an accurate thermal model. A simple model of the honeycomb as two radiating sheets with a known gap distance will be the first model of the CFRP honeycomb sheets. This assumes that the aluminum honeycomb core is relatively non-participating which may not necessarily be a good assumption. However, the fact that aluminum's emissivity is relatively low compared with that of CFRP, along with the fact that the honeycomb is very thin, means we should be able to neglect conduction along the honeycomb and use a purely radiative model to create an equivalent thermal conductivity.

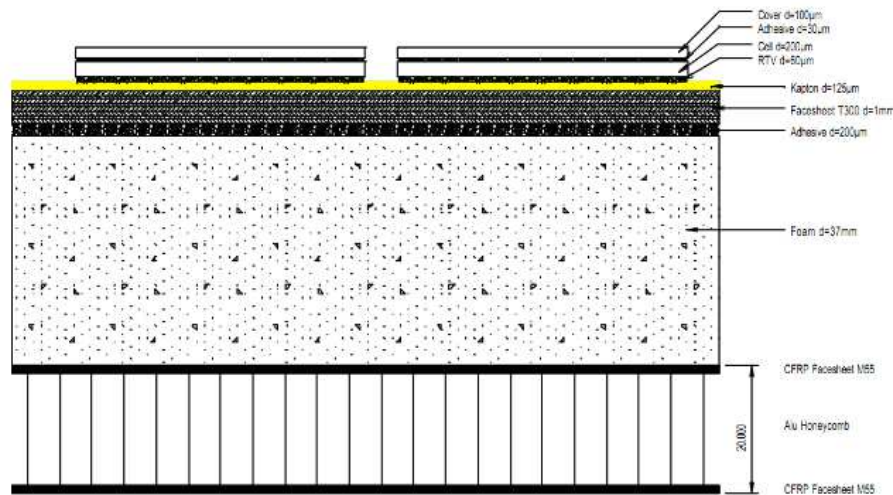


Figure 2: A Cross-section of the solar panel/foam/aluminum honeycomb insulation used in the GRACE satellite system. Image from GR-DSS-DID-0003 Issue 8 Rev A, page 21 of 45.

Information on the packing, density, and thermal mass of the aluminum honeycomb was unavailable. Modeling the CFRP as two plates in COMSOL would just increase the computation time unnecessarily. Instead, I applied the density and heat capacity of the foam. To compute the conductivity I used an analogy with conduction along with radiation equations from “Thermal Radiation Heat Transfer” (Howell and Siegel) p. 215.

Model of Radiation Between Two Infinite Plates

$$\frac{q}{A} = \frac{\sigma * (T_1^4 - T_2^4)}{1/\epsilon_1 + 1/\epsilon_2 - 1} \approx k_{eqv} * \frac{(T_1 - T_2)}{L}$$

For temperature data we could use any available information, however, since I was working on the cold case I pulled the ambient temperatures from GR-DSS-TN-0009.

$$\begin{aligned} T_{inside} &= 268K \\ T_{outside} &= 353K \\ \epsilon_{CFRP} &= 0.9 \\ k_{foam} &= 0.004 \left(\frac{W}{m * K} \right) \\ L_{foam} &= 37mm \\ L_{al.} &= 20 \sim 40mm \end{aligned}$$

Now, setting the heat flux through the foam equal to that of the CFRP honeycomb and solving the non-linear radiation equation we get both a positive and negative conductivity. Taking the positive value to be the actual conductivity we get the equivalent conductivity of CFRP aluminum honeycomb to be approximately

$$k_{eqv.} = 0.071 (W/m * K)$$

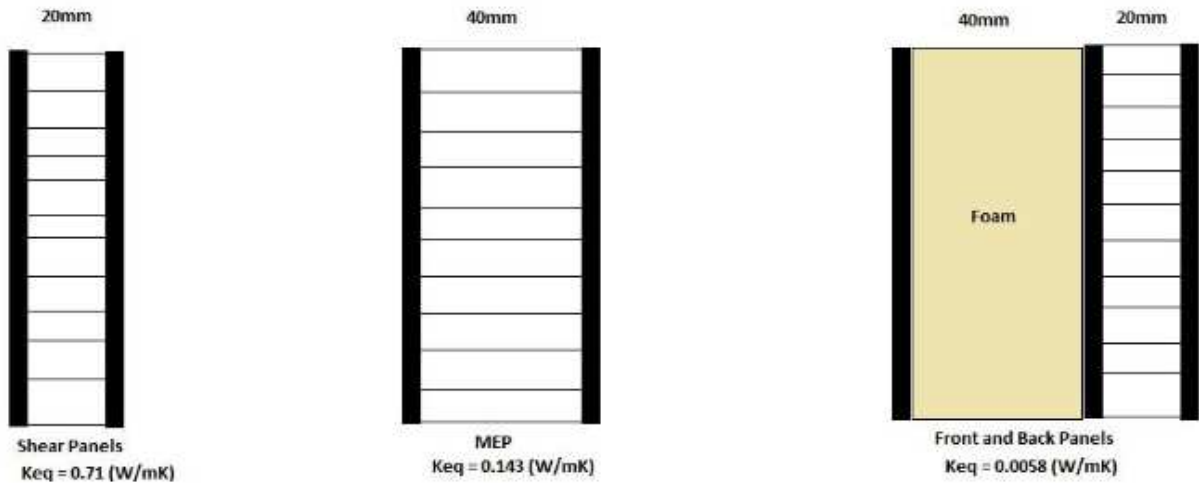


Figure 3: The models currently being used to account for the CFRP in the COMSOL model. The solar array and the front panels are modeled with separate methods for comparison of the results. However, due to computational concerns the lumped foam + CFRP aluminum honeycomb model may be used even if it's slightly less accurate because it significantly reduces modeling time.

A second major point of contention was the specification of thermal conductivity (k). Clearly from the heat equation, conductivity may be anisotropic. When dealing with materials like carbon fiber sheets, assuming isotropic conductivity is questionable because of the great difference in conductivity of CFRP based on the fiber direction. The current COMSOL model assumes isotropic conductivity based on tabulated values from the ASME Handbook. These assumptions will be checked in the future to see if the COMSOL model accurately predicts the actual satellite temperature profile. Additionally, most satellite components have been given a conductivity of 100 (watts/m*k) which is to assume they are lumped in nature. This clearly is a modeling assumption as the

components vary widely in composition and function. However it greatly simplifies the modeling of the satellite and will be an assumption that needs to be checked in the future especially for the heat channels that connect components to radiators.

$$Biot \# (Radiation \text{ Analogy}) = \frac{\epsilon \sigma (T + T_{\infty})(T^2 + T_{\infty}^2) * Volume}{k_{iso} * A_{surf}}$$

$$Biot \# (PCDU) = \frac{\epsilon \sigma (298K + 273K)(298K^2 + 273^2) * .0175(m^3)}{k_{iso} * .4044(m^2)} \approx \frac{.23}{k_{iso}}$$

We see that a choice of thermal conductivity 100 (watts/m*k), the Biot number << 0.1 which should allow us to use the lumped capacitance method. Lower temperatures, smaller volumes and greater surface area also improve the validity of our assumption. Future work will focus on validating these assumptions for CFRP sheets where thermal conductivity is certainly anisotropic.

Creating the Thermal Environment

Perhaps the most time consuming and difficult problem was developing a simple system to account for the movement of the GRACE satellite around the earth. This model should account for different orbit heights, solar conditions, albedo, etc.. I chose to place a coordinate system on the GRACE satellite where a ray would be pointed at the sun and the angle of that ray with the normal of each exterior surface could be used to calculate the solar flux. This method has the advantage of being simple to modify in the future with a basic knowledge of dot products and also allows for arbitrary orbits which would not be possible using the simple beta orbit angle. One of the main draw backs to this system is the careful application of trigonometry is required to properly specify the heat flux on a

surface. Additionally, any modification of the satellite which would change the normal of a surface will require modification of the equations governing heat flux on that surface. These problems may be overcome in the future with various other solar environment models, but for now this is the least computationally intensive model available.

To replace the beta angle specification, I created a coordinate system centered with the satellite with +Z pointing towards the main GPS antenna, +Y towards the backup GPS antenna, and +X defined by the right hand rule of cross products +Y to +Z. This coordinate system is defined by two unique angles phi (Φ) and gamma (γ). Then any vector of unit length defined from a surface in reference to the phi-gamma coordinates will have the vector defined by the following. This vector is considered to be pointing “at” the sun and the dot product with the normal vector of a surface then defines the angle χ which, along with the cosine law and the surface absorptivity, defines the incident heat flux on any exterior surface.

The beta angle is defined by the angle between a vector originating from the sun and the plane inscribed by the orbit of a satellite around the earth. This method of defining the relationship with the sun would prove cumbersome because the satellite moves inside of a fixed coordinate system.

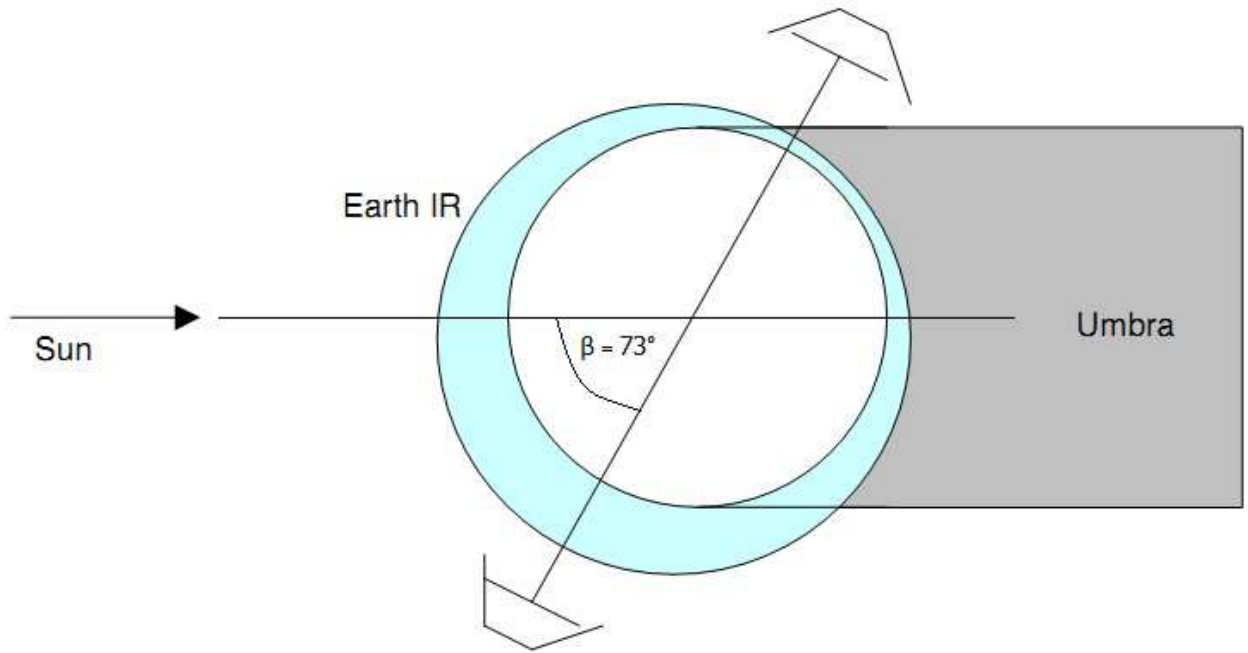


Figure 4: Beta angle described as a function of satellite orbit about the earth. This method creates 180 unique orbit possibilities but has proved difficult to implement in COMSOL. (GR-DSS-TN-0009)

$$\text{Vector } \vec{B} \text{ Pointing at the Sun} = \sin(\theta)\sin(\gamma)\hat{x} + \sin(\theta)\cos(\gamma)\hat{y} + \cos(\theta)\hat{z}$$

$$\text{Surface Normal} = A_x\hat{x} + A_y\hat{y} + A_z\hat{z}$$

$$\cos(\chi) = (A_xB_x + A_yB_y + A_zB_z)/|A||B|$$

$$\text{Surface Heat Flux } \left(\frac{\text{Watts}}{\text{m}^2} \right) = q_{\text{solar}} * \varepsilon * \cos(\chi)$$

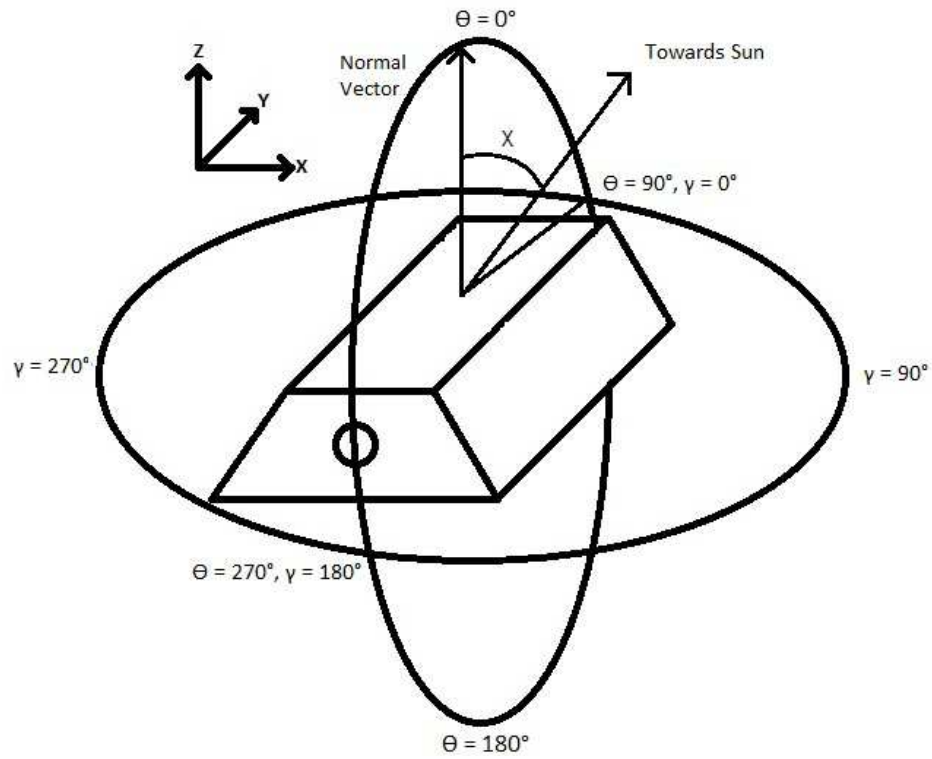


Figure 5: The Phi Φ and Gamma γ coordinate system in reference to the satellite. Round circle on the front panel is the K-Horn Antenna. Angle X defined as the angle between the sun and the normal vector of any surface of the satellite.

In addition to the sun vector derived from the above coordinate system, I've calculated the sun vector as a function of beta angle and orbit period which should help when relating the thermal analysis to other GRACE researchers.

$$\text{Vector } \vec{B} \text{ Pointing at the Sun} = -\sin(\beta)\hat{x} - \cos(\beta)\cos(\tau)\hat{y} - \cos(\beta)\sin(\tau)\hat{z}$$

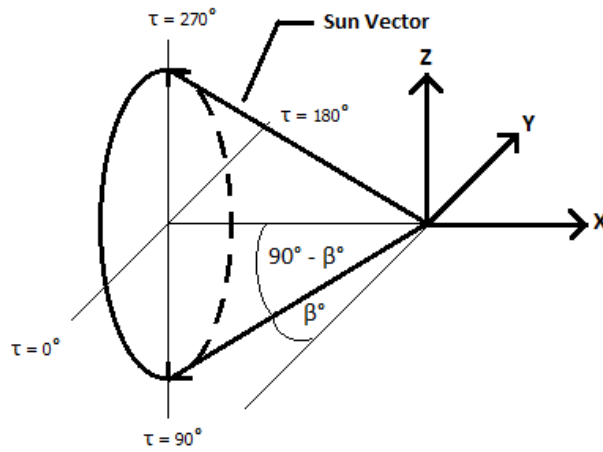


Figure 6: The sun vector $f(\beta, \tau)$ calculated with respect to the COMSOL GRACE coordinate frame.

The sun facing vector is extremely important in the recent versions of COMSOL where it controls the direction of incident solar radiation. This removes the need for computing the angle of incident sunlight with the normal vector of a surface. The Boolean functions are only required to turn off the incident solar radiation when the satellite would be moving into the Earth's umbra. The $f(\beta, \tau)$ controlling the incident solar radiation is dictated by the satellite's orbit the user models.

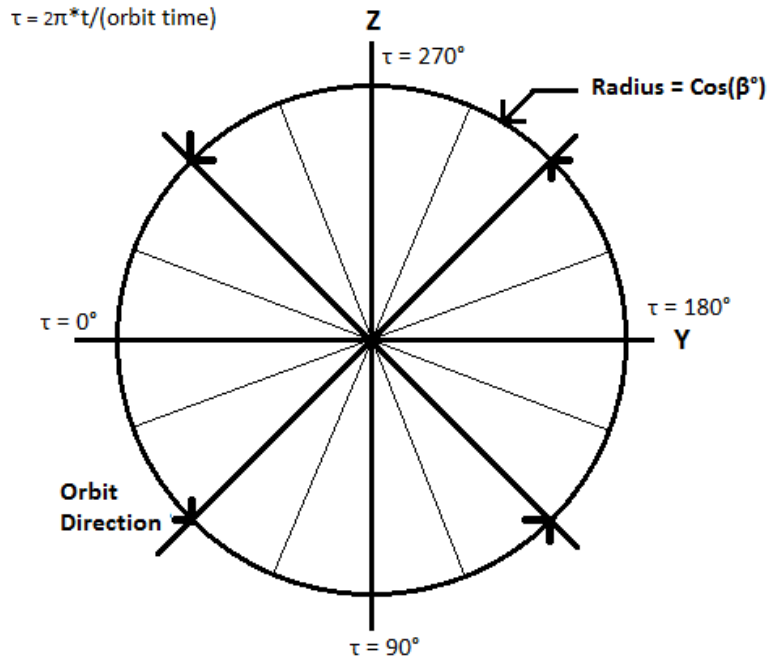


Figure 7: Expansion of the Z, Y coordinate plane with respect to the sun vector expressed as $f(\beta, \tau)$. The X component of the sun vector with respect to the defined coordinate system is a constant function of β which significantly simplifies the calculations.

In COMSOL 4.1 and 4.2, an external infinite distance radiative heat flux can be created in the “Heat Transfer” physics model. Specifying the direction of the heat flux as $f(\beta, \tau)$, and using Boolean logic statements to turn the flux off when the satellite would pass through the Earth's umbra have led to significant increases in model fidelity. Now any arbitrary $f(\beta, \tau)$ can be computed and we no longer need to keep track of surface normal to account for solar radiation. The drawback is no longer being able to independently specify absorptivity and emissivity on the surface. However, given that the

values for absorptivity and emissivity on the exterior surface are quiet close, this should not be a large issue.

To calculate the view factors and $f(\beta, \tau)$ for which the satellite would be in the Earth's umbra, I reference geometry and "Radiation Heat Transfer" <J. R. Howell>. The cut off angles were used in Boolean logic statements to shut off the solar heat flux to surfaces when geometrically those surfaces would be shadowed by the Earth or satellite. All exterior surfaces would need a logic statement including view factors with Earth, the angle with the sun vector for which the surface normal would be in the shadow of the satellite, and the angle with the sun vector for which the entire satellite would be in the Earth's Umbra.

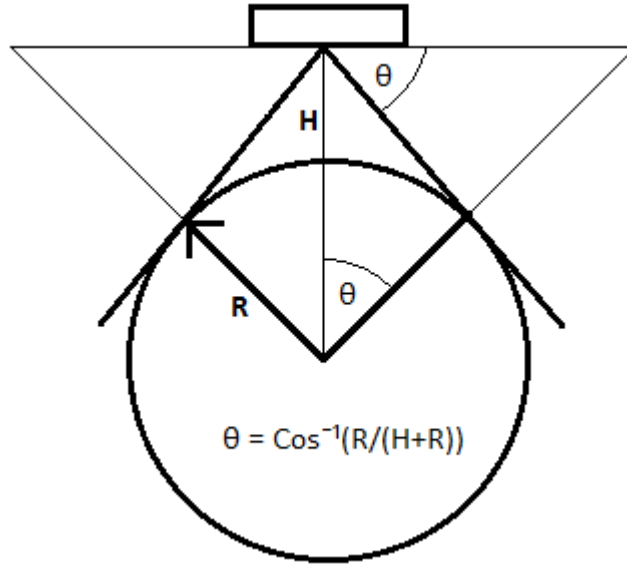


Figure 8: Derivation of the angle at which the earth blocks the sun from the satellite.

Radius of the earth is approximately 6370km while the orbit height varies from 300km to 500km. Values of Θ_{cutoff} range from 22° at 500km to 17.25° at 300km.

With the sun vector and normal vectors specified in terms of either the GRACE coordinate system or $f(\beta, \tau)$, we address the presence of the Earth using Boolean logic statements to turn the heat fluxes on and off depending on the current direction of the sun vector. This was implemented in COMSOL by the multiplication of a logic statement with the heat flux and can easily be adjusted in the future. To address the Earth I calculated the cutoff angle beyond which the shadow of the earth blocks the satellite from the sun. I also used the direction of the sun vector along with Boolean logic expressed as trigonometric expressions to suppress the $\text{Cos}(\chi)$ term when it would produce negative values.

$$\begin{aligned}
& -Y \text{ Front Panel Heat Flux } \left(\frac{\text{Watts}}{\text{m}^2} \right) \\
& = q_{\text{solar}} * \varepsilon * \cos(\chi) * (\sin(\theta) \geq 0) * (\cos(\theta) \geq -0.375) * \cos(\gamma) \\
& \leq 0)
\end{aligned}$$

View factors with the radiator were also calculated and a heat flux was applied to the radiator to account for Earth IR and albedo. Changing the radiator would require reapplying the heat flux.

Controlling the Thermal Environment by Coordinate System

In COMSOL 4.0a, heat flux's had to be controlled by Boolean functions.

Mapping the vector parallel to the face of a surface to a unit circle makes it simple to create the Boolean function in an intuitive way. Here I've mapped the parallel face of the exterior foam surface of the GRACE satellite where the K-Horn rests to the 0° of a unit vector circle. To set the limits of the Boolean function we recognize that from 0° to 180°, if there were no obstructions, sunlight could fall directly onto the exterior surface. To account for the Earth's surface, using facing factors or geometry, we recognize that sunlight would not be blocked at any angle from 270°-22° to 90°+22° or. The overlap of these two regions outlines the angles at which sunlight can fall on the exterior side of the satellite accounting for the Earth's umbra.

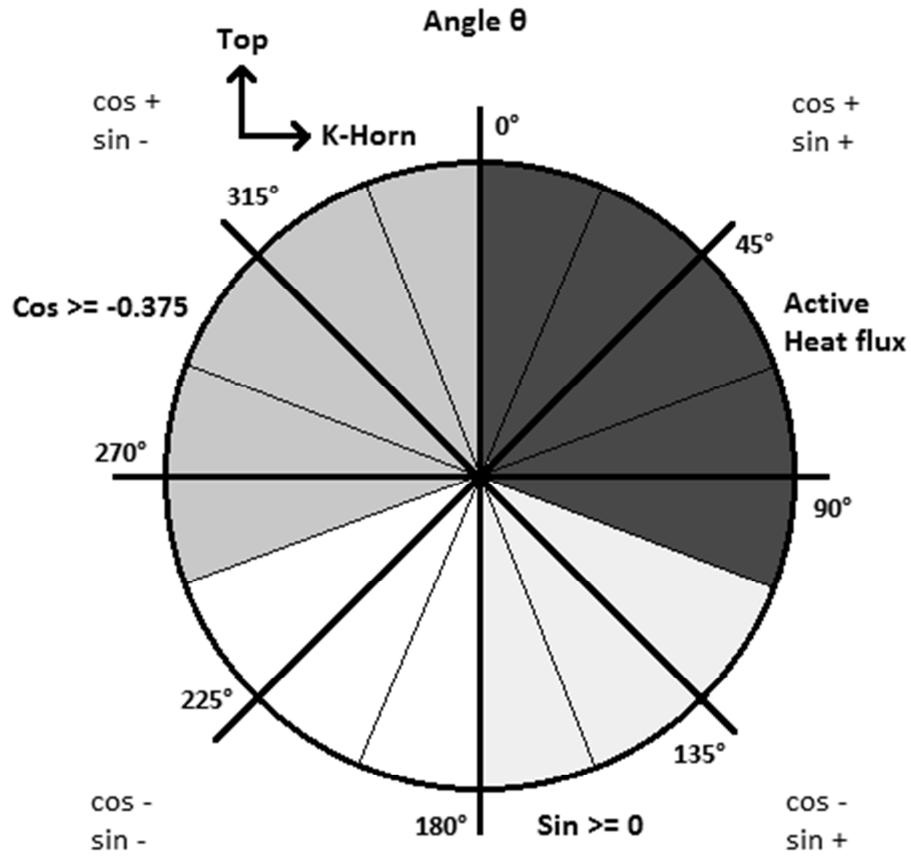


Figure 9: Derivation of the Boolean logic governing the heat flux on the $-Y$ front panel.

The overlapping region of *cos* and *sin* creates the appropriate region of solar heating.

The calculations of Boolean logic expressions using normal vectors, sun vectors, and active heat flux angles were performed for all sides of the GRACE satellite. The newer versions of COMSOL did not require this calculation but it may prove useful in the future. The newer versions use an infinite distance radiation source controlled by a vector indicating the normal direction of the heat flux.

To guarantee the proper thermal environment, older COMSOL models export all relevant angles and Boolean functions to an excel file which can be used to debug any errors. Common errors were accidentally specifying $f(\beta, \tau)$ in reverse, mistakenly modifying the Boolean logic functions, removing the heat flux from a surface or accidentally specifying the solar heat flux +/- an order of magnitude. Most of these issues have been resolved in later versions of COMSOL which uses an infinite distance radiation source to create the thermal environment.

Meshing the Model

COMSOL makes meshing very simple compared to most programs. Using the default meshing system, I applied a tetrahedral mesh to each satellite component. Lumping components of similar dimensions significantly reduces meshing errors and makes it much easier to lower or raise the polygon count. A higher polygon count gives better accuracy but requires significantly more computer resources. A polygon count between 7,000~14,000 converges in less than an hour per orbit and gives +/- 1K repeatability for the basic satellite model. The default settings work well for simple geometries without curves or thin components. The mesh can be set from extremely fine to extremely coarse. Coarse settings seem to work best without significantly affecting the repeatability of results.

To deal with thin components custom settings had to be applied for each thin object including advanced mesh settings. Finding the correct mesh size for small objects is a balance of maximum and minimum polygon size along with resolution in narrow regions. Trial and error seemed to be the only way to find a good fit that did not create a

meshing error. When every component was adequately meshed, solutions could be computed.

Running Steady State and Transient Cases

Actually running the model is quiet simple in COMSOL. I specified the desired number of satellite orbits, the thermal environment and the solution tolerance for a case and allowed the solver to automatically converge on an answer. Run times could be between 5 minutes for a steady state solution and 90 minutes for a three orbit cycle [Intel i5 2600, 4Gb RAM] . Raising the solution tolerance from 0.01 to 0.1 actually resulted in failure of the model to converge to a solution. I believe the non-linear nature of the radiation transfer equation demands each step of the solution retain a certain level of accuracy or the T^4 term may converge on the wrong answer. Lowering the solution tolerance from 0.01 to 0.001 gave no increase in accuracy but increased the computation time by an order of magnitude. The initial conditions used for the COMSOL model is simply a uniform 20°C but temperature profiles from previous runs or any arbitrary conditions can be used to speed up model run times. I have not found using a temperature profile to be worth the hassle to save a small amount of computational time.

Chapter 5: Analyzing the Results

To verify the computer model I used a number of “sanity checks” looking for suspicious results in the data. Some of the tests were as simple as setting the outside environment to a specific temperature and turning off all the internal and external heat sources in the model. The temperature of every part in the model should then converge to the ambient environment temperature.

To test the application of heat flux was working correctly, I created a separate model with parallel plates of known size and shape which could easily be calculated from known cases (See Siegel and Howell, appendix). If the computer calculated heat flux matched reasonably with the analytical solution then the check was considered a success and the heat flux would be applied to the actual satellite model.

Testing the coordinate systems was a major part of modeling the thermal environment. Because of the difficulty of programming with sin, cos and their related functions multiple tests were used to assure no singularities existed which might cause the model to create large positive or negative heat fluxes. Additionally the values of the phi, gamma, beta and tau with respect to time were exported along with the data and verified for accuracy. These tests resulted in multiple logic statements to correct issues with multiple solutions to spherical coordinate system modeled with only two angles. To verify the satellite model as a whole was operating according to energy conservation, the heat fluxes at every external surface were calculated and, along with internal heat generation, verified to be net zero. This test also provided valuable insight into where the next GRACE satellite might improve the thermal efficiency of its design. Area Weighted Temperature Average

Data from the model is recorded for each time step of the transient model or just the final solution of the steady state solution. The temperature data is an average temperature of the entire surface over the time step of the transient model. This makes it difficult to match the temperature data from the COMSOL with the previous thermal models. The interior surface of the outer foam insulation interfaces with the interior of the satellite and a small part with the Earth and space. Modifying the .stl file or carefully creating surface temperature probes in the model could rectify this issue but it does not affect the trends of the temperature.

Comparing with Previous Models

To compare the COMSOL model with the previous thermal models, I created excel files comparing the minimum, maximum, average and spread of the temperatures from each satellite component with the previous models. Areas where the COMSOL model's max, min and average temperature all fell outside of a +/- 10°C region were highlighted for review.

	Results (C)			Hot 73 Survival		
Name	Max	Min	Average	Δ Max	Δ Min	Δ Average
ACC ICU	24	20	22	5	2	4
ACC SU	20	20	20	6	5	6
Batterys	20	18	19	7	6	6
IPU	28	20	26	15	6	13
K-Horn Assembly	20	16	18	13	9	12
MEP Nadir Side average	20	14	16	5	-1	1
MEP Zenith Side average	20	13	15	5	-3	0
OBDH	28	20	25	2	-6	0
PCDU	20	9	14	0	-11	-7
Radiator average	22	10	16	27	15	21
RFEA	40	20	35	14	-6	9
Sampler Unit	20	1	8	6	-13	-6
SCA +Y Exterior	75	22	56	72	19	53
SCA +Y Interior	47	20	38	34	7	24
SCA -Y Exterior	19	-22	-19	-21	-63	-59
SCA -Y Interior	20	-9	-5	-2	-31	-27
Solar Array +X inside average	20	7	11	6	-6	-2
Solar Array +Y inside average	32	17	26	14	0	9
Solar Array -Z inside average	20	13	16	4	-3	0
Solar Array -X inside average	19	9	12	3	-7	-4
Solar Array -Y inside average	18	-26	-6	1	-44	-24
Solar Array +X outside average	46	-55	-19	91	-10	26
Solar Array +Y outside average	13	-145	-135	154	-5	5
Solar Array -Z outside average	16	-128	-69	84	-60	-1
Solar Array -X outside average	32	-49	-18	78	-3	27
Solar Array -Y outside average	107	28	85	23	-57	0

Table 1: Hot Survival case with $\beta^\circ=73^\circ$. During calibration of the satellite model the highlighted rows (yellow for hot, blue for cold) had no temperatures within the uncertainty of the previous computer models. The “Results” is from the COMSOL model and the Hot 73 Survival is from the 2nd Computer Model.

The actual satellite telemetry would be the judge of whether a temperature was correct therefore there was no immediate concern that the temperatures of certain satellite components did not match with the previous computer models from DaimlerChrysler. I found the COMSOL model matched well with the old computer models for the interior satellite components but had difficulty matching the predicted exterior satellite temperatures. This most likely resulted from NEVADA being capable of independently

specifying emissivity and absorptivity. It seems that COMSOL using emissivity = absorptivity is a bad assumption but the effects should be minimal through the foam insulation.

Various thermal cases were analyzed by the previous computer models. I compared the COMSOL model results with the tabulated results from GR-DSS-TN-0009. The trends matched well with most temperatures falling within +/- 10°C. This validated the COMSOL model compared with the previous computer models. The results are stored as individual COMSOL files for future review.

Parameter	Hot 1	Hot 2	Hot 3	Cold 1	Cold 2
Purpose	Determination of maximum temperatures Radiator size	Determination of maximum temperatures Radiator size	Determination of maximum temperatures Radiator Size	Determination of minimum temperatures Critical heater power	Determination of minimum temperatures Critical heater power
Solar constant	1420 W/m ²	1420 W/m ²	1420 W/m ²	1320 W/m ²	1320 W/m ²
Albedo factor	0.3	0.3	0.3	0.2	0.2
Average earth IR	260 W/m ²	260 W/m ²	260 W/m ²	215 W/m ²	215 W/m ²
Orbit height	300 km	300 km	300 km	500 km	500 km
Sun-to-orbit plane angle	0°	45°	73°	0°	90°
Thermo-optical properties	EoL	EoL	EoL	BoL	BoL

Table 2: Various cases from the old computer models to compare with the new COMSOL model

Chapter 6: Comparing with the Real Telemetry

Satellite telemetry obtained from the Center for Space Research was used to judge the accuracy of the COMSOL model. Dr. Bettadpur provided a “Parameter Table Query” listing the names of available satellite data feeds recorded daily by the CSR. Data on the thermal environment, heater operation and orbit position of the satellite was organized by β° for quick comparison with the COMSOL model. Two cases were tested for accuracy; $\beta^\circ=73^\circ$ and $\beta^\circ=45^\circ$. This should provide a maximum temperature case and a case with a large time spent in the Earth's umbra respectively. For each case, 16920 seconds (3 satellite orbits) worth of data was extracted from the satellite telemetry for comparison.

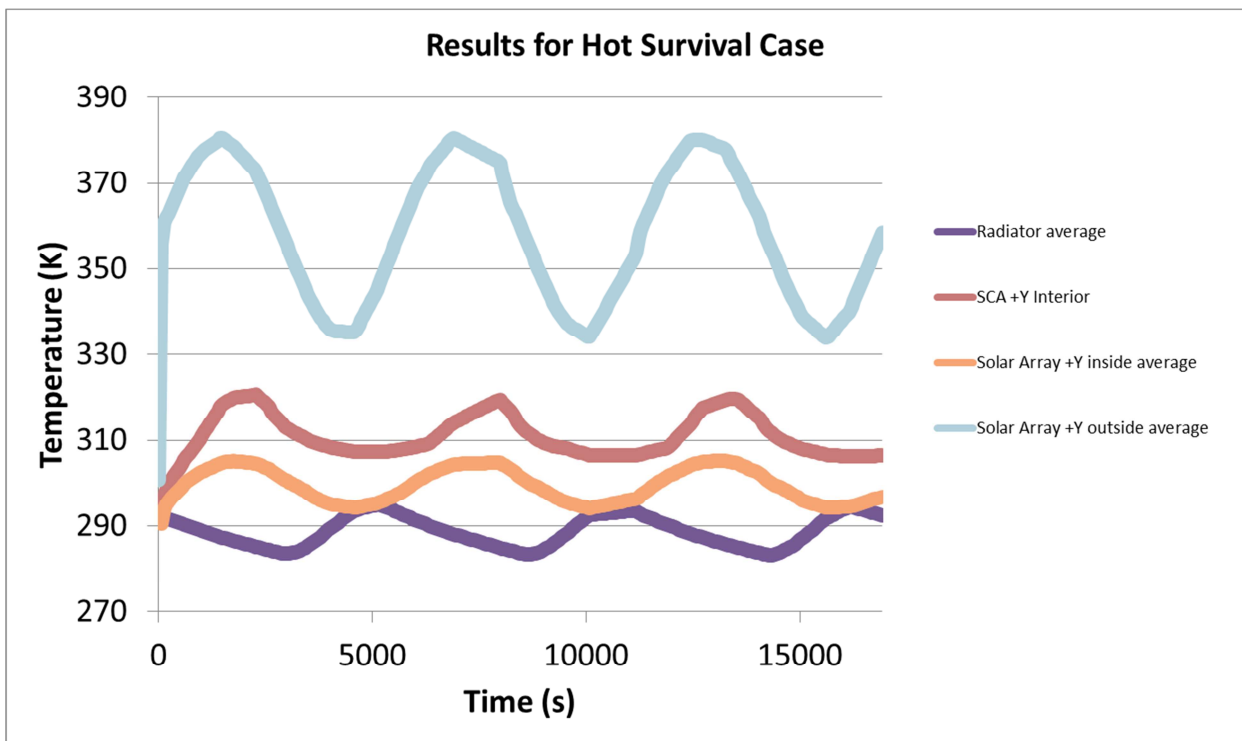


Figure 10: Hot Survival $\beta^\circ=73^\circ$ transient results after 3 orbits. Charts like these reveal a great deal about the satellite thermal design. Here we see the fast transient response of the

external satellite components and the decoupled transients between the radiator and the other satellite components.

Analyzing the results of the Hot Survival case I created this example chart showing 4 important temperature profiles of the radiator, star camera baffle, and the primary heated side of the exterior foam insulation. Comparing the interior and exterior temperature of the +Y Solar Array insulation with the radiator, it is apparent the radiator is not governing the interior temperature of the satellite. The fact that the transients of the radiator do not match with the transients of the insulated +Y Solar Array suggests to me the primary mode of heat transfer into the satellite is from the insulation and not the radiator. The main equipment platform (not shown) is preventing the radiator from moderating the temperature within the part of the satellite with the instruments. More worrisome is the effect of the SCA +Y Baffle which went unaccounted for in the previous NEVADA analysis and matches the thermal transients of the interior. I believe this is causing significant heating and cooling (on cold cases) within the satellite. The fact that the interior SCA Baffles are covered in CFRP (emissivity of 0.9) also leads me to believe they are a significant source/sink of heat within the interior of the satellite. The decoupling of the radiator and the coupling of the SCA Baffles were consistent in all tested cases.

Discussion on Model's Accuracy

The components and materials not listed in GR-DSS-TN-0009 either did not have properties specified in the thermal documents, were under specified, or simply not listed. The total mass of the satellite was listed as 475kg, however, only 136kg of satellite components were fully specified in GR-DSS-TN-0009. Some additional mass would be the foam insulation, aluminum honeycomb panels and radiator which had properties specified in other documents. A significant point of concern lies with the wiring of the satellite which would be difficult to implement but may account for a significant amount of thermal mass. The current model assumes that the wiring is non-participatory and special attention will be paid in the future to see if this assumption is valid when comparing the COMSOL model with the actual flight data. The thermal models show a small transient that would likely be unaffected by the increased thermal mass of the wires.

Material properties are a huge source of uncertainty. Surface radiative properties are typically +/-20% and the ones provided by Astrium were only specified as a single number without specifying what method was used to find the thermal properties. Conductivity for all the parts was not given so approximations and estimates for CFRP and aluminum honeycomb were made and calibrated from the previous computer models. Instruments were lumped into solid objects based on the thermal properties derived by DaimlerChrysler so there is no way to be sure if my instrument temperatures are comparable to previous computer models. Finally, being able to specify emissivity and absorptivity (possible in newer COMSOL versions) would increase the fidelity of the COMSOL model.

Chapter 7: Conclusions

The COMSOL model accomplished the goals of creating a new satellite model that accurately predicts the thermal environment of the GRACE satellite. The model is robust enough to handle all possible cases from the actual satellite telemetry and can be used for experimenting with the thermal environment for a new satellite. Two key features of the current satellite have been identified for redesign using this model. The radiator has proven to be thermally decoupled from the instrument bay of the satellite. This is partly due to the MEP preventing significant heat transfer to the radiator and partly due to insufficient thermal insulation of the foam supporting the solar panels.

Future GRACE Satellite designs should focus on insulating the exterior foam panels of the satellite to decouple the interior thermal environment from the solar irradiation. The MEP and radiator should be redesigned to take advantage of the stable earth IR. Currently the radiator is insensitive to emissivity changes and the MEP prevents the satellite components from stabilizing with the Earth's IR, instead creating a cyclical thermal environment with the poorly insulated foam siding. It would also be extremely important to review the SCA baffle design. It was not accounted for in the NEVADA computer model and only later added to the second computer model by DaimlerChrysler. The large outer baffle is painted black on the interior and exterior which seems to create a large heat source/sink in the main body of the satellite. Simply wrapping the baffles in MLI might remove some temperature fluctuation from the satellite. Better coupling with the radiator should reduce the power consumption of the heaters.

Better tabulation of the material data will be necessary for any new GRACE satellite. Better values for foam conductivity, surface emissivity, surface absorptivity and a good model for aluminum honeycomb heat transfer could greatly improve the thermal modeling of the GRACE satellite. CFRP covered aluminum honeycomb makes up the MEP and supports the foam insulation, but there is almost no data on its approximate conductivity. On the next satellite, the methods of measuring conductivity and surface properties should also be presented to help quantify uncertainty in the computer model.

It is my hope this COMSOL model serves as a guide for future researchers and engineers to design an improved GRACE satellite. I regret being unable to quantify many uncertainties in modeling the original GRACE satellite. The model presented is robust enough to model the trends and approximate thermal environment of the current GRACE satellite. If improvements in tabulated material properties are made a new model could give significantly better data. With all previous models, data, telemetry and documentation stored on an external hard drive, I submit this report, model and results along with written documents as the final product of my GRACE thermal model.

Bibliography

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